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Determination of the Effect of Walking on the  
Forced Convective Heat Transfer Coefficient  
Using An Articulated Mannikin

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## Abstract

This study addresses the effect of the walking motion on local convective heat transfer coefficient at various body sites, employing an articulated mannikin. The forced convective heat transfer coefficient ( $h_c$ ) is determined by the naphthalene sublimation plate technique. Circular naphthalene disks were affixed to various body segments of the articulated mannikin. The mannikin then simulated walking at four different gaits (0.5-2.0 mi/hr, or 0.2-0.9 m/sec) under constant temperature (30°C) and wind speed (0.4-0.7 m/sec depending on the body segment) in an environmental chamber. The amount of naphthalene weight loss through sublimation was translated to  $h_c$  using the Chilton-Colburn analogy between heat and mass transfer. The results showed that arm movement during walking, unexpectedly, diminished the effective local convective transfer coefficient. Increased gait (from 0 to 2.0 mi/hr) actually resulted in a decrease in  $h_c$ , as measured on the arms and legs. On the nonmoving body trunk, no significant difference in  $h_c$  was observed with increased gait. When the mannikin was held stationary and the chamber wind speed increased, a corresponding increase in  $h_c$  was observed. Thus, during walking, motion of the swinging limbs, the "pendulum" or "pumping" effect, tends to decrease the forced convective heat transfer coefficient as observed locally on the limbs. For the walking gaits applied in this study, a 5-7% decrease in  $h_c$  was observed.

Keywords: Convective heat transfer, Articulated mannikin, Walking motion effect, Naphthalene sublimation, Heat-mass transfer analogy

## INTRODUCTION

The effect of the swinging appendages during walking and running has been characterized as the "pendulum" effect [Clark et al, 1974], or the "pumping" effect [Vogt et al, 1983; Olesen & Madsen, 1983]. Clark et al [1974] studied evaporative and dry heat loss of an athlete running outdoors, and reported that the local convective heat transfer coefficient could be increased by at least a factor of two, from  $21.8 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$  to  $53.8 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$ , as a result of the extra velocity of the limb relative to the trunk. Although they mentioned that the effective evaporative coefficient would also be increased by the "pendulum" effect, they did not quantify the increase, nor attempted to separate the convective and evaporative components of this effect. Vogt et al [1983] studied the "pumping" effect on clothing insulation using human subjects. Olesen & Madsen [1983] and Olesen et al [1982] performed a similar study using a movable thermal mannikin. Complicated by the extra layer of clothing and the microclimates the layer created, the results were inconclusive. Vogt's data showed that the "pumping" effect may increase or decrease the resultant clothing insulation depending on the air temperature. Olesen et al [1982, 1983] reported negligible change in thermal insulation value between sitting and cycling.

This study focuses on how walking motion affects the convective heat transfer coefficient of forced flow. The effect of arm and leg swing on  $h_c$  was investigated using an articulated mannikin. A mannikin offers the advantage of exact and repeatable motion. A mannikin also avoids the problem of perspiration and eliminates any evaporative contribution usually involved in exercising human subjects. Convective coefficient  $h_c$  is determined using a modification of the naphthalene sublimation technique [Nishi & Gagge, 1970], based on heat and mass transfer analogy, independent of any energy and metabolism measurement.

## METHOD & THEORY

Heat-mass transfer analogy of a sublimating substance has been traditionally used to accurately predict the forced convective heat transfer coefficient [Sogin, 1958; Neal, 1974]. Naphthalene very conveniently sublimates at room temperature and thus has been used by a number of investigators to experimentally determine  $h_c$ . Sparrow & Tien [1977, 1979] studied forced convection to a square plate at different yaw angles. Sogin [1958] applied jet stream normally to naphthalene disks. Nishi & Gagge [1970] attached naphthalene balls to different body segments on human subjects. The convective transfer of the ball was then related to the corresponding body segment by approximating the body segment as a cylinder and using the known convective relationship between ball and cylinder.

In our study, circular naphthalene disks were attached to the surface of various body segments on a lifesize (1.68 m<sup>2</sup>) articulated mannikin. The naphthalene disks were appropriately curved to conform to the corresponding body segment curvature. Air flow was directed normally at the disk surface. Since the naphthalene disk conforms to the body segment curvature and sits directly over the specific body site, the local  $h_c$  over the specific site is measured, rather than an average  $h_c$  for the entire body segment. Scaling of results to translate from cylinder to ball, and extrapolation of body diameter and shape from cylinder study thereby become unnecessary.

### Heat - Mass Transfer Relationship

Mass transfer of naphthalene sublimation  $h_m$  can be expressed as [Nishi & Gagge, 1970]

$$h_m = R \cdot T_a \cdot \dot{m} / (P_s - P_a) \quad \{1\}$$

$h_m$  = naphthalene mass transfer coefficient (m/sec)  
 $\dot{m}$  = measured naphthalene sublimation loss per surface area (Kg/m<sup>2</sup>·sec)  
 $T_a$  = ambient temperature (K)  
 $P_s$  = naphthalene surface vapor pressure (mmHg)  
 $P_a$  = naphthalene vapor pressure in air (assumed = 0)  
 $R$  = naphthalene gas constant (0.487 mmHg·m<sup>3</sup>/kg·K)

Assuming that the heat of sublimation is negligible,  $P_s$  may be considered as equal to the saturated vapor pressure at  $T_a$  [Sherwood & Trass, 1960],

$$\log_{10} P_s = 11.55 - 3765/T_a$$

or

$$P_s = 10^{(11.55 - 3765/T_a)} \quad \{2\}$$

$P_s$  in mmHg,  $T_a$  in K

The Chilton-Colburn analogy j-factor [ASHRAE Handbook Fundamentals 1985] can be described:

$$\text{for heat transfer } j_h = \frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3} \quad \text{where, } Pr = \frac{c_p \cdot u}{\kappa} \quad \{3\}$$

$$\text{for mass transfer } j_m = \frac{h_m}{u} (Sc)^{2/3} \quad \text{where, } Sc = \frac{u}{\rho \cdot D_v} \quad \{4\}$$

$h_c$  = heat transfer coefficient  
 $Pr$  = Prandtl's number  
 $\rho$  = density  
 $c_p$  = specific heat  
 $\kappa$  = thermal conductivity

$h_m$  = mass transfer coefficient  
 $Sc$  = Schmidt's number  
 $D_v$  = mass diffusivity  
 $u$  = air velocity

Equating heat and mass transfer j-factor,

$$\frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3} = \frac{h_m}{u} (Sc)^{2/3}$$

or

$$h_c = \rho \cdot c_p \left( \frac{Sc}{Pr} \right)^{2/3} \cdot h_m \quad \{5\}$$

### Experiment

The articulated mannikin at the US Army Research Institute of Environmental Medicine, is capable of simulated walking up to 80 steps/min. Length of the leg stride and arm swing are individually adjustable. For this experiment, five walking gaits of 0 (stationary), 0.5, 1.0, 1.5, and 2.0 mi/hr (0-0.9 m/sec) were applied. The environmental chamber was set at  $T_a = 30^\circ\text{C}$ , with dew point at  $5^\circ\text{C}$  (relative humidity  $\approx 20\%$ ). The regional air velocity ranges between 0.4 to 0.7 m/sec at different body segments of the mannikin. The duration of each experiment was 55 minutes. The regional temperature and air velocity were measured at five sites: upper arm, lower arm, thigh, calf and chest. Figure 1 gives a schematic representation of the locations of naphthalene disk on the mannikin. Hot wire anemometers and thermistor temperature probes (TSI Anemometer Tree System) were placed approximately 2 cm above and 3 cm away from the naphthalene disk, in such a way as not to disturb the impinging air flow to the disk. Air flow is directed normally at the disks.

Scintillation grade naphthalene with a melting point of approximately  $80^\circ\text{C}$  was poured into casting disk cassettes, which were modified from camera lens covers. The castings quickly hardened at room temperature. The cassettes were appropriately curved to conform to surface curvature of the upper arm,

lower arm, thigh and calf of the mannikin. Casting cassettes used for the chest were not curved. The curved cassettes expose an elliptic rather than circular surface. The elliptic surface area of each cassette disk was measured and properly quantified during evaluation of the  $\dot{m}$  term of eqn. {1}. The disks were mounted into vinyl retainers which were in turn fastened to the mannikin with Velcro straps. The square vinyl sheets have a circular hole cut in the middle. Circumference of the hole was slightly smaller than the disk cassette, such that each cassette snapped tightly into the retainer. Immediately after casting, the disks were stored individually in air-tight containers. All naphthalene disks were allowed to equilibrate in the chamber at 30°C for 24 hours before using. The disks were weighed immediately before and after an experiment, on a balance sensitive to  $\pm 0.01$  mg (Mettler AE163).

## RESULTS

Table 1 shows the regional air velocity with the mannikin assuming a stationary position. This level of regional wind speed was maintained throughout the experiment. Also shown are the local  $h_c$  at the specific sites, measured and computed using eqns. {1}-{5}. For each study run,  $h_c$  was averaged over the 55 minute experiment period. The results in Table 1 are the average of 15 runs.

Figure 2 gives the local  $h_c$  at the five naphthalene disk sites: upper arm, lower arm, calf, chest and thigh. The five walking speeds were 0 (standstill), 20, 40, 60 and 80 steps/min, which translate to gaits from 0 to 2 mi/hr (0-0.9 m/sec). Student's T-test were evaluated between the stationary position  $h_c$  and  $h_c$  at each of the four gaits, to determine if the difference was significant. In Figure 2, t-values from the T-tests are also included. A t-value  $> 2.101$  indicates that the decrement is significant, with  $p < 0.05$ .

The four walking gaits were 0.5, 1.0, 1.5 and 2.0 mi/hr (0.22, 0.45, 0.67, and 0.89 m/sec). However, the arm swing and leg stride of the articulated mannikin were set at different lengths, to represent a natural human walking motion. The upper arm disk and lower arm disk necessarily experience different motion because they attach on different portions of the arm swing arc. A similar condition exists for disks attached to the leg. Therefore, the equivalent forward velocity experienced by the disks were different than the walking gaits. The resultant linear velocity as experienced by the naphthalene disks at the four walking gaits are summarized in Table 2. The mannikin walked at 20, 40, 60 and 80 steps/min. Linear velocities were calculated using the full swing length of 13 cm, 31 cm, 16 cm and 51 cm for the disk mounted on the upper arm, lower arm, thigh and calf, respectively. Table 2 represents only the singular effect of walking. The chamber air velocity, shown in Table 1, is an additional factor that interacts with the disk linear velocity during walking.

To further ascertain that the decrement in  $h_c$  as shown in Figure 2 was indeed due to the walking motion and not artifact, another set of experiments were performed without the complication of limb movement. Figure 3 gives the data obtained when the mannikin was held stationary, but with the chamber wind speed set at levels comparable to the walking gaits.

## DISCUSSION

Rapp [1972] defined the free and mixed convection region as that where ambient air velocity is  $< 0.2$  m/sec. Hence, from Table 1, the experimental conditions in our study were well into the forced convection region. The measured  $h_c$  should therefore be predominately  $h_c$  from forced air flow. Nishi & Gagge [1970] reported for subjects undergoing free walking at 4 mph (6.4

m/sec), that the regional  $h_c$  at the arms and legs were 16-17 W/(m<sup>2</sup>·°C). They operated at a normal ambient air movement of 0.15~0.2 m/sec. Considering that chamber air velocity in this study was between 0.4-0.7 m/sec, the range of  $h_c$  shown in Table 1, 22-23 W/(m<sup>2</sup>·°C), appears to be in a reasonable range when compared to their original work.

Figure 2 gives the regional  $h_c$  at the five naphthalene disk sites, upper arm, lower arm, calf, chest and thigh; at the five walking speeds, 0, 20, 40, 60 and 80 steps/min. On the upper and lower arms, there is clearly a decreasing trend for  $h_c$  as the mannikin walking speed increased from 0 to 80 steps/min. Decrease in  $h_c$  was between 5 to 7%. The t-value from Student's T-test showed each decrement to be statistically significant. In contrast, for the chest site,  $h_c$  stayed quite constant, and t-value showed no statistically significant difference between gaits. The motion of the arm apparently caused a decrease in the forced convective heat transfer coefficient evident perhaps from localized wind currents at these sites. Although the exact mechanism is not apparent, one possible explanation could be that the naphthalene disks experienced nonuniform air flow during the arm swing cycle. On the forward stroke of the arm swing, the naphthalene disks were moving in the opposite direction to the chamber air flow. The air flow that the disks encountered was enhanced (a vector sum). Conversely, on the backward stroke of the arm swing, the arm and chamber air flow were in the same direction. Air flow experienced by the disk was therefore diminished (a vector difference). Naphthalene sublimation rate, hence  $h_c$ , does not vary linearly with changing air velocity [Nishi & Gagge, 1970]. The effect of a vector sum (forward stroke) and a vector difference (backward stroke), not surprisingly, do not cancel each other. The measured  $h_c$  thus is rationally a combination of the two effects, averaged over the 55 minute study period. At present, we can

only ascertain the average air velocity from the data. Our anemometers do not have fast enough response time to distinctly measure the different air velocities that must exist on the forward and backward strokes. An investigation with faster response anemometers to study the air velocity variation during each arm swing is contemplated.

On the calf, a 7% decrease in  $h_c$  was also evident. Here, however, we found that  $h_c$  did not further decrease after walking speed of 60 steps/min, but rather, showed an increase at 80 steps/min. From Tables 1 and 2, chamber air velocity on the calf (1.537 mi/hr, Table 1) and local linear velocity of the calf disk at 80 steps/min (1.520 mi/hr, Table 2) became comparable. It could be that at a point before the two speeds become comparable, the combined vector sum and vector difference yielded a minimum average air flow over the disk, hence a minimum  $h_c$ . This minimum should also exist for the upper arm and lower arm cases, but the articulated mannikin walking speed could not be fast enough to reach this point of minimum. A faster response anemometer should also facilitate the determination of this minimum point.

The thigh data in Figure 2 showed no particular pattern. One peculiarity about the thigh data is also evident in Nishi & Gagge's [1970] results. Comparison of Nishi & Gagge's Tables 3 and 4 showed that on the bicycle ergometer, increase in  $h_c$  paralleled the increase in air movement on the thigh. However, with free walking,  $h_c$  is  $\approx 25\%$  lower on the thigh than other sites, e.g. upper arm and legs with similar air movements. Nonetheless, relative motion of the limbs could still be the determinant. Only, this time, there were two relative motions involved. It can be seen from the schematic representation of Figure 1, the naphthalene disk on the thigh was at the same level as the hand. As the mannikin walked, the hand swung in opposite direction to the thigh. Movement of the hand could thus disturb the impinging

air flow over the thigh disk. On a bicycle ergometer, presumably the arms do not swing in opposite directions to modify air flow over the thighs. In our study, relative motion of the arm and leg could have generated a very complex air flow pattern over the thigh disk, the result of which can not be visualized from only averaged anemometer data.

Data in Figure 3 were obtained with the mannikin held stationary, and the chamber air speed set at levels comparable to the walking gaits. On a standstill mannikin,  $h_c$  from all five naphthalene disks increased accordingly with increasing chamber air velocity. The observation that it is the walking motion that decreases the effective local  $h_c$ , is further reinforced.

Another implication of the above result is that when human subjects are used in a study, the evaporative heat loss could be a much more significant factor than Clark et al [1974] had suggested. The naphthalene sublimation method measures only the convective heat transfer. Also, since a mannikin does not perspire, all evaporative processes, such as evaporation and any contamination of naphthalene by sweat, are eliminated. Assuming that the pendulum motion of the limbs indeed doubles the heat loss as described by Clark, and pure convective heat loss, as found in this study, is decreased rather than increased by the pendulum effect, then the major bulk of the increase in heat loss during walking and running, in humans, must be evaporative rather than convective in nature.

### Conclusion

This study looked at the effect of walking on the convective heat transfer coefficient of forced air flow. It was found that walking, or the motion of the swinging limbs during walking, generally decreased the forced  $h_c$  as measured on the arms and legs. For the walking gaits applied in this study, a 5-7% decrease in  $h_c$  was observed. This amount of decrease in  $h_c$ , displayed in Figure 2, must represent, quantitatively, the "pumping"/"pendulum" effect. It was also learned that faster response anemometers are needed to further investigate in detail the mechanism that caused the  $h_c$  decrement.

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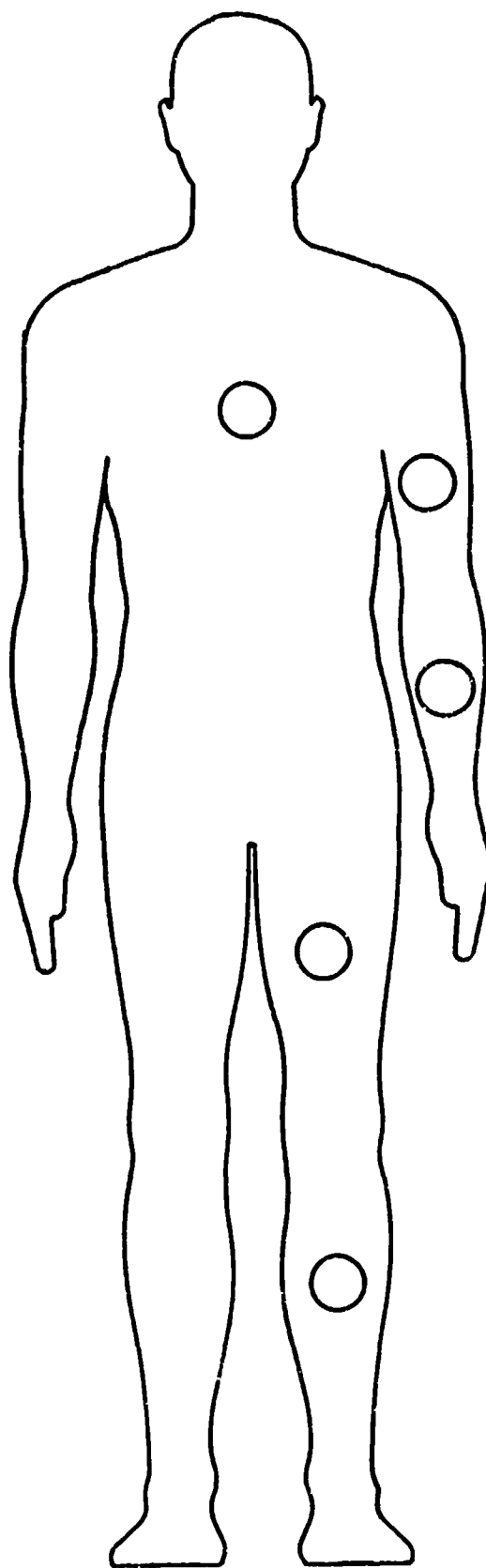
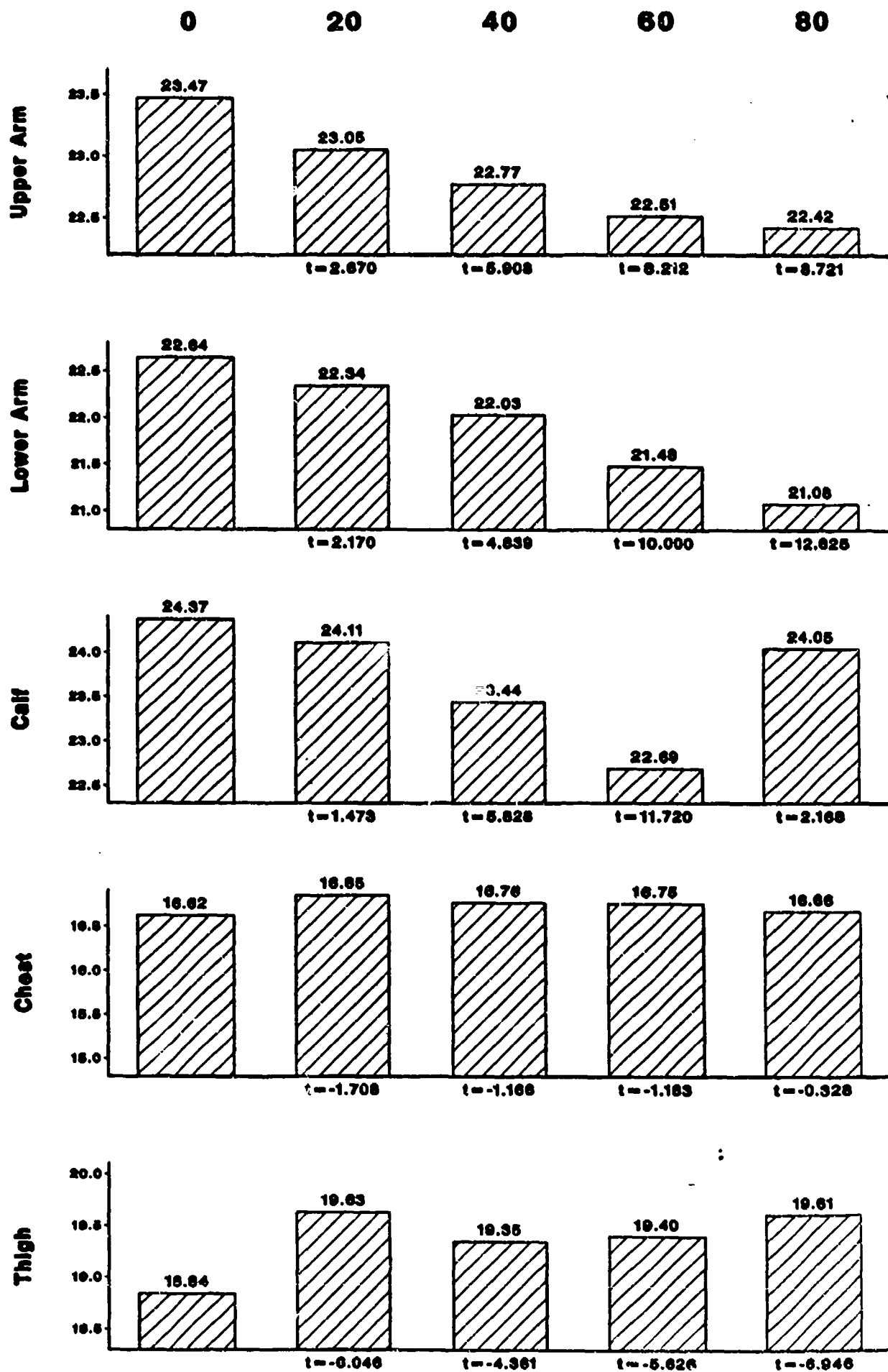


Figure 1 Schematic diagram showing locations of the naphthalene disk on the mannikin

naphthalene disk site	regional air velocity	local $h_c$ $W/(m^2 \cdot ^\circ C)$
Upper Arm	1.354 $\pm$ 0.036 mi/hr (0.605 $\pm$ 0.016 m/sec)	23.47 $\pm$ 0.42
Lower Arm	1.592 $\pm$ 0.024 mi/hr (0.712 $\pm$ 0.011 m/sec)	22.64 $\pm$ 0.39
Thigh	0.933 $\pm$ 0.031 mi/hr (0.417 $\pm$ 0.014 m/sec)	18.84 $\pm$ 0.34
Calf	1.537 $\pm$ 0.052 mi/hr (0.687 $\pm$ 0.023 m/sec)	24.37 $\pm$ 0.52
Chest	1.093 $\pm$ 0.028 mi/hr (0.489 $\pm$ 0.013 m/sec)	16.62 $\pm$ 0.38

Table 1 Regional air velocity and local  $h_c$   
on the articulated mannikin  
at the sites of the naphthalene disk

**Figure 2 Convective Heat Transfer Coefficient  $h_c$**



full swing length		walking speed (steps/min)			
		20	40	60	80
Upper Arm	13 cm	0.097 mi/hr (0.043 m/s)	0.194 mi/hr (0.087 m/s)	0.291 mi/hr (0.130 m/s)	0.387 mi/hr (0.173 m/s)
Lower Arm	31 cm	0.230 mi/hr (0.103 m/s)	0.463 mi/hr (0.207 m/s)	0.693 mi/hr (0.310 m/s)	0.924 mi/hr (0.413 m/s)
Thigh	16 cm	0.119 mi/hr (0.053 m/s)	0.239 mi/hr (0.107 m/s)	0.358 mi/hr (0.160 m/s)	0.477 mi/hr (0.213 m/s)
Calf	51 cm	0.380 mi/hr (0.170 m/s)	0.761 mi/hr (0.340 m/s)	1.140 mi/hr (0.510 m/s)	1.520 mi/hr (0.680 m/s)

Table 2 Local linear velocity as seen by the naphthalene disks  
as result of the walking motion

**Figure 3  $h_c$  with stationary mannikin at increasing chamber air velocity**

